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ФИЗИКО-МЕХАНИЧЕСКИЕ СВОЙСТВА НЕАВТОКЛАВНОГО ЗОЛЬНОГО ПОРИЗОВАННОГО БЕТОНА

В.В. Белов, Т.Р. Баркая

Владимир Владимирович Белов

Кафедра производства строительных изделий и конструкций, Тверской государственный технический университет, наб. Аф. Никитина, 22, Тверь, Российская Федерация, 170026

E-mail: vladim-bel@yandex.ru

Темур Рауфович Баркая

Кафедра конструкций и сооружений, Тверской государственный технический университет, наб. Аф. Никитина, 22, Тверь, Российская Федерация, 170026

E-mail: btrs@list.ru

В работе изложены принципы малоэнергоемкой технологии неавтоклавного поризованного бетона (НЗПБ) на основе топливной золы. После затворения водой и перемешивания в обычном смесителе сырьевая смесь заливается в формы или опалубку, где вспучивается и затем твердеет в нормальных условиях или с небольшой тепловой обработкой.
Использование НЗПБ с такой же средней плотностью, как у обычных легких бетонов на обжиговых заполнителях, для армированных несущих конструкций может быть оправдано близкими значениями общей пористости и связанными с ними показателями упругих и деформативных свойств, а также аналогичными условиями работы арматуры в этих изделиях. В то же время по сравнению с газозолобетонами НЗПБ выгодно отличаются большей стабильностью свойств при изготовлении, меньшим расходом газообразующих добавок, а по сравнению с обычными легкими бетонами – отсутствием дорогостоящих крупных пористых заполнителей.
Определены прочностные и деформативные характеристики НЗПБ как при кратковременных, так и при длительно действующих нагрузках, что является базой для дальнейших исследований применения этого перспективного материала в несущих и ограждающих конструкциях.

Ключевые слова: *неавтоклавный газобетон, топливная зола в качестве наполнителя, малоэнергоемкая технология, прочностные и деформативные характеристики*

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PHYSICAL AND MECHANICAL PROPERTIES OF NON-AUTOCLAVE ASH POROUS CONCRETE

V.V. Belov, T.R. Barkaya

Vladimir V. Belov

Department of Construction Products and Structures Production, Tver State Technical University, 22 Af. Nikitin Quay, Tver, 170026, Russia

E-mail: vladim-bel@yandex.ru

Temur R. Barkaya

Department of Constructions and Facilities, Tver State Technical University, 22 Af. Nikitin Quay, Tver, 170026, Russia

E-mail: btrs@list.ru

The work describes the principles of low-energy technology of non-autoclave porous concrete (NAPC) based on fuel ash. After closing with water and mixing in a conventional mixer, the feed mixture is poured into molds or formwork, where it swells and then solidifies under normal conditions or with little heat treatment.
The use of NAPC with the same average density as conventional light concretes on roasting aggregates for reinforced bearing structures can be justified by the close values of the total porous steel and the associated elastic and deformative properties, as well as similar working conditions of reinforcement in these products. At the same time, compared to gas-ozone concrete, NAPC is advantageously characterized by greater stability of properties during manufacture, lower consumption of ha-z-forming additives, and compared to conventional light concrete — the absence of expensive large porous aggregates.
Strength and deformation characteristics of NAPC are determined both at short-term and long-term active loads, which is the basis for further research on the use of this per-special material in bearing and enclosing structures.

Key words: *non-autoclave gas concrete, fuel ash as filler, low-energy technology, strength and deformation characteristics*

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INTRODUCTION

It is arguably better to use lightweight concrete instead of heavyweight concrete in load-bearing structures because of the reduced load from the dead weight of structures, which provides savings in reinforcement and concrete itself. For large engineering structures and multi-storey buildings, the transition from heavy concrete to structural lightweight concrete makes it possible to reduce the cost of foundation erection [1]. At the same timethe reduced concrete density for load-bearing and enclosing structures gives additional heat protection of internal premises and allows for easier operation of the structures themselves, which shows the importance of such materials [2].

Reducing the cost of lightweight concrete structures is possible by not using expensive porous aggregates and as well as porosing concrete mix during the production that leads to a concrete structure unique due to a large number of small closed pores, which in turn leads to the high-water resistance and frost resistance. Methods of porization of concrete mixture based on the use of air-entraining additives such as CNV, as well as blowing agents, with their relatively small consumption do not allow to significantly reduce the density and material intensity of structures, and with a large number of additives, on the one hand, expensive (due to high cost and scarcity of additives themselves), and on the other hand, are characterized by complexity of concrete (foamed concrete technology).

Currently, due to the rising cost of energy resources, there is a strong interest in mineral building materials with high thermal insulation properties. Such materials include non-autoclave porous concrete [3, 4]. The non-autoclave porous concrete interests the manufacturers and researchers with low energy consumption, wastelessness, and environmental friendliness [5]. However, the shrinkage of non-autoclave porous concrete in the process of drying can reach 2-3.5 mm/m. It is significantly influenced by the properties of the interporous partition [6], which are largely determined by the microstructure optimized with fine mineral additives, which ultimately has a positive complex effect on the technology and properties of thermal insulation materials [7]. For example, phosphogypsum additive in the composition of non-autoclave porous concrete plays the role of not only a filler, but also an activator [8]. A decrease in the shrinkage of this material with an increase in the content of mineral additives instead of a portion of cement has been established at the same time [9].

Reinforcement with highly dispersed basalt fibers can compensate the main drawbacks of conventional concrete — low tensile strength and brittleness (insufficient cracking resistance) [10], and, obviously, reduce shrinkage. [11] has investigated and analyzed the following concrete shrinkage reduction methods: use of cement with reduced heat dissipation, steel fibers, polypropylene fibers with their pre-moistening, lightweight aggregate pre-saturated with water. Notably, when natural lightweight aggregate with grain size of 2-4 mm pre-saturated with water was used, the shrinkage of 28 days old high strength concrete was reduced by about 48% compared to the reference concrete, with no change in compressive strength [11].

Development of strength of plasticized cement stone made with superplasticizer C-3 of 1.0 to 0.25% concentration to cement mass at constant B/C, just like 0.27%, indicates that the strength of plasticized cement stone can be both higher and lower than that of the control composition [12]. There is a technology that does not allow shrinkage deformations in obtaining gas concrete wall stones based on waste crushed concrete by casting technology with an average density of 650-750 kg/m^3 with an optimal structure [13]. After drying non-autoclave porous concrete, shrinkage can reach 2.0-3.5 mm/m [14].

Further cheapening of such structures is possible due to the use of local industry waste in the composition of concrete and, first of all, ash from TPPs. Porous concrete is not inferior to brick and expanded clay aggregate concrete in performance indicators, and in some cases it exceeds them in frost resistance and heat protection. The production cost of porous concrete products is 50% lower than that of lightweight concrete products. While energy prices rise, the efficiency of gas ash concrete will increase in comparison with concrete on aggregates requiring high-temperature treatment [15]. Manufacturers already know how to obtain reinforced structures based on gas ash concrete [16].

However, non-autoclave porous concrete 900-1200 kg/m^3 dense is not regulated enough compared to slag and expanded clay aggregate concrete 1600-1800 kg/m^3 dense. Until now, there are no indicators of long-term deformability, data on the dynamics of strength and thermal properties, information on the behavior of steel reinforcement in products made of these concretes, etc. In many cases, this makes it impossible to use non-autoclave porous concrete instead of firing aggregate concrete, and in general it sharply limits the application area of the former for load-bearing reinforced concrete structures [13]. This problem could be solved with a new material — non-autoclave ash porous concrete (NAPC) 1600-1700 kg/m^3 dense based on gas concrete technology, but with less gas forming additives. NAPC of the same average density as that of ordinary lightweight concretes on firing aggregates for reinforced load-bearing structures should be used due to close values of total porosity and related indices of elastic and deformative properties, as well as similar working conditions of reinforcement in these products. At the same time, in comparison with gas-isolated concretes, NAPC will favorably differ with higher stability of properties during manufacture, lower expense of gas-forming additives, and in comparison, with usual light concretes — absence of expensive large porous aggregates.

EXPERIMENT

To obtain NAPC, a silica component was used — a waste product of local industry, fly ash from Tver TPP-4. Bulk density of ash from TPP-4 varies from 700 to 1300 kg/m^3. The specific surface area is 800 to 1200 cm^2/g. The true grain density is 2.02 to 2.5 g/cm^3. According to the classification, ash from TPP-4 is classified as fine-grained. According to the content of CaO and MgO, as well as SO_3, ash meets the standards. The ash from TPP-4 is not compliant with requirements on specific surface, which required special measures to use it as an ash aggregate for manufacturing cellular concrete.

Another silica component was sand for construction works according to GOST 8735.

Calcium oxide or quicklime with a mass fraction of calcium oxide of at least 85% is used as an alkaline additive. In addition, to increase the plasticity of all mixes for the injection molding method, SP-1 superplasticizer additive was introduced in the mixing water in a constant amount of 1.5% of the cement weight. The mixing water was heated to a temperature of 60-65 °C before molding the samples.

PAP-2 aluminum powder was used as a gas forming agent.

A B-D$_{13}$ non-linear three-factor planned experiment was used to select the optimum composition of non-autoclave ash porous concrete (NAPC). Variables: mass fraction of ash in ash-sand mixture A/(A+S), amount of gas educator additive — aluminum powder in relation to mass of cement A and watercement ratio W/C varied in the following limits: A/(A+S) = 0÷0.6; A = 0.07÷0.11%; W/C = 0.57÷0.69. Cement to aggregates (ash and sand) mass ratio was constant and equal 1: 2.3.

The cellular concrete mixture was prepared as follows: cement, previously dried and sifted through a sieve with a mesh size of 5 mm ash and sand, and mixing water were loaded into the mixing vessel. The mixture was stirred using a propeller stirrer at 150-200 rpm for 2 min. Then, the density of the unporous concrete mixture was determined using a measuring vessel of 1 dm^3 and the fluidity of the mixture by the size (diameter) of the flake with a Suttard viscometer. Then the mixture was unloaded into the mixing vessel again, the calculated amount of aluminum suspension was added and stirred for another 1 min, after which it was poured into 10 cm cube shapes with an edge of about 90% of their height.

Two hours after pouring the mixture into the molds (porization of the mixture usually ended after 30-40 min), the samples were placed in the steaming chamber. After hardening of samples in the steam chamber for 8 hours at a temperature of isothermal exposure of 85 ° C, they were demolded and tested.

As the criteria for optimization of NAPC composition, the average density of samples in dry state, compressive strength, coefficient of structural quality was used calculated by the formula

$$ККК = \frac{R_{сж}}{\gamma_0},$$

where R_{cmp} is the compressive strength, MPa; γ_0 is the relative density of concrete samples (in relation to water density), dimensionless value.

The experimental data revealed the coefficients of mathematical models of dependences of properties of concrete mixture and concrete from the factors of the form specified above

$$y = v_0 + v_1x_1 + v_2x_2 + v_3x_3 + v_{11}x_1^2 + v_{22}x_2^2 + v_{33}x_3^2 + v_{12}x_1x_2 + v_{13}x_1x_3 + v_{23}x_2x_3,$$

where $x_1 = 3.33(A/A + S – 0.3)$; $x_2 = 50(A – 0.09)$; $x_3 = 16.7(W/C – 0.63)$.

The coefficients of mathematical models of dependencies are given in Table 1.

Dependences of dry density of NAPC samples, plotted according to mathematical models, on factors of material composition show that increasing the content of aluminum powder A, the share of ash in sand-ash mixture A/(A+S), and water-cement ratio W/C reduce the density of samples in dry condition. At the same time, the compressive strength and structural quality factor dependences are more complicated and are unique due to the presence of local extremes.

In order to determine the optimal composition of NAPC corresponding to the highest values of R_{cmp} and KKK, the optimization problems of these dependencies were solved. The optimal variables corresponding to the maximum coefficient of constructive quality were: A/(A+S) = 0.465; A = 0.084%; W/C = 0.57. The ultimate compressive strength of 28 days old NAPC is 15.2 MPa, density in the dry state is 1600 kg/m^3. According to the results of research on the composition of NAPC, it was decided to use structural non-autoclave ash porous concrete in the production of trial samples of NAPC and determine their physical and mechanical properties, including the effect of long-term loading on the properties of the micro-cracking process of this material.

It is known that during compression of concrete elements at the initial stage, there is some compaction of material caused by healing of microcracks. With further loading, the process of micro-cracking begins to prevail over compaction of concrete, as a result of which its structure becomes less homogeneous, and the time of passage of the ultrasonic wave increases. The load, at which the ultrasonic wave transit time increment changes sign, corresponds to the first parametric point R_{t0}. This level of loading determines the beginning of intensive microcracking [17]. The process is accompanied by noticeable inelastic creep deformations. When the level of the second parametric point R_t is reached, microcracking processes are accelerated, and the creep deformation of concrete passes into the non-linear region.

Tests were conducted on standard ash-concrete prisms with dimensions 10×10×40 cm. Six prisms were tested.

The tests were conducted in accordance with GOST 17624 methods. The device UK-10PMS and transducers with a resonance frequency of 60 kHz were used to measure ultrasound propagation time in concrete. The method of end-to-end sounding has been applied. To ensure reliable contact between the concrete and the working surfaces of ultrasonic transducers, liquid glass was used. The results are shown in Table 2 and Fig. 1.

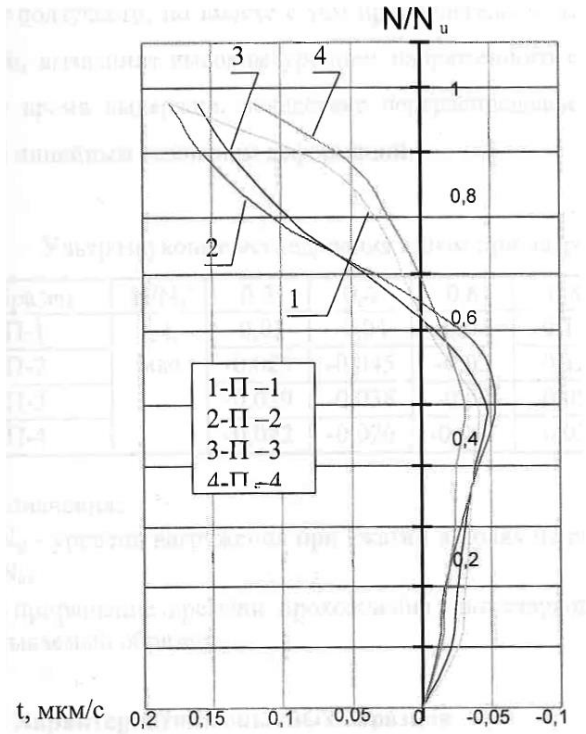

Fig. 1 Dependence of ultrasonic wave transit time on loading level

Table 1. *Coefficients of mathematical models of dependencies of properties of concrete mixture and ash porous concrete on composition factors*

Indicators	Factors									
	v_0	v_1	v_2	v_3	v_{11}	v_{22}	v_{33}	v_{12}	v_{13}	v_{23}
Density of the unperforated mixture, kg/m^3	2204	−28.5	−14.9	−7.5	−58.4	22.0	−109.4	−54.2	8.1	−50.6
Suttard flow diameter, cm	12.9	−4.3	−0,07	1.4	2.1	−1.7	−0,05	−0,5	−2.0	0.4
Density of concrete samples in dry state, kg/m^3	1616	−66.1	−97.4	−70.0	22.0	−21.5	−42.5	−49.1	−61.6	−38.1
Strength of concrete samples, MPa	9.6	0.13	−1.5	−1.5	−0.56	−1.15	−0.59	−0.46	−0.50	−0.54
Coefficient of structural quality	5.91	0.26	−0.65	−0.78	−0.38	−0.71	−0.26	−0.10	−0.13	−0.30

Table 2. *Ultrasonic tests of prisms under loading*

Sample	N/N_u	0.2	0.4	0.6	0.8	0.95
P-1	Δ t, μs	-0.03	-0.04	-0.01	0.11	0.16
P-2		-0.025	-0.045	-0.03	0.12	0.18
P-3		-0.029	-0.038	-0.02	0.05	0.12
P-4		-0.022	-0.026	-0.017	0.03	0.12

Notation:

N/N_u is the level of compressive loading in fractions of the breaking load N_u;

Δt is the increment of time of ultrasonic waves transit through the tested sample.

Long term load tests were also carried out. Special spring units were developed at CaS Department of TvSTU for the long term tests of concrete prisms with dimensions 10×10×40 cm. Creep deformations in concrete prisms were determined according to the conventional methodology by excluding unloaded twin samples from the total deformations, shrinkage deformations. Shrinkage deformations were measured on unloaded prisms. Shrinkage and creep deformations were measured by clock type indicators with the division value of 0.002 mm, installed on two opposite sides of the samples.

The free shrinkage deformations of concrete were measured throughout the test period, as well as the ambient temperature and humidity (Fig. 2).

RESULTS AND DISCUSSION

Analysis of the curves in Fig. 1 shows that in non-autoclave ash porous concrete, the variation of the transit time and respectively the velocity at loading levels corresponding to the occurrence of parametric points is insignificant. This peculiarity of deformation of the considered material can be explained by its considerable porosity.

Based on the position of critical points, two loading levels should be specified for the main samples — 0.6 and 0.75 of the breaking force. At 0.6, the state of the concrete is such that the creep strain is mostly linear. Load level 0.75 was supposed to provide intensive creep deformation, but at the same time it was supposed that nonlinearity of creep caused by high stress level would be replaced by linear development of deformations after some soaking time due to redistribution of stresses.

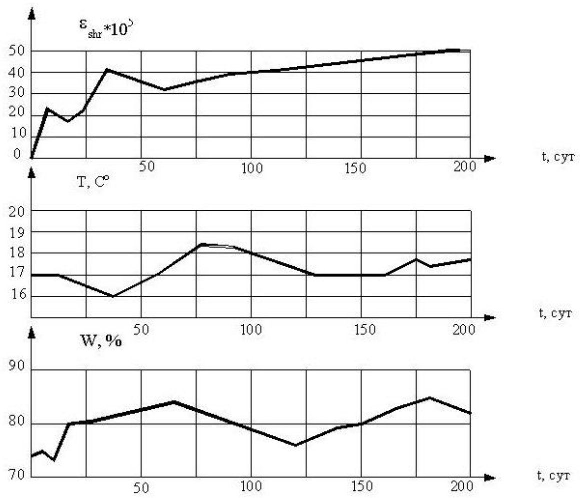

Fig. 2. Changes over time in relative humidity, temperature, and shrinkage deformations of concrete

The unique aspects of shrinkage deformation development in time shown in Fig. 2 show that the growth of their absolute values practically stopped after 150 days after starting the measurements, and their further changes are mainly determined by the change of air humidity.

In Fig. 3, curves characterizing development of deformations (characteristics) of concrete creep, obtained from results of long-term tests of concrete prisms loaded in different ages at two levels *of long-term acting load, are: 65 and 75% of the force corresponding to the NAPC prism strength.*

Table 3 shows their numerical values for different levels and ages of loading and observations.

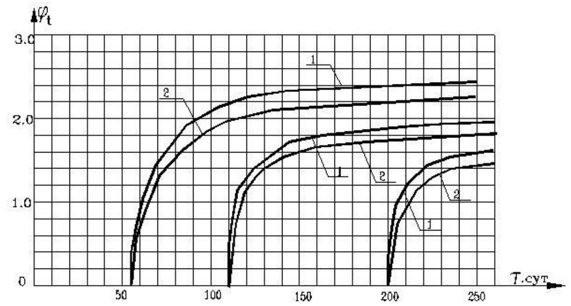

Fig. 3. Time variation of NAPC creep characteristics φt as a function of age τ and loading time T: 1 — 75% load of the short-term destructive force; 2 — same, 60%

The nature of the curves in Fig. 3 shows a pronounced dependence of φ_t values on the age of concrete. However, the development in time of properties of creep at loading at ages τ_1 = 50, 120, 200 days is practically identical.

For all observed ages, the curves of creep properties have one feature in common — rapid, during the first day, flow of deformations and then their exponential increase with approximately the same rate. The magnitude of rapid creep deformation is very significant and ranges from 30 to 40% of the full, i.e., limit, values for the moments of time when the damping becomes obvious.

Thus, NAPC of the same average density as that of ordinary lightweight concretes on firing aggregates for reinforced load-bearing structures should be used due to close values of total porosity and related indices of elastic and deformative properties, as well as similar working conditions of reinforcement in these products.

***Table 3.* Elastic deformation ε_{be}, creep deformation ε_{pl}, and creep properties φ_t of concrete at different loading ages τ_1**

Age of concrete at the moment of loading τ_1, days.											
55				120				200			
t-τ_1, days	ε_{be} ×10^5	ε_{pl} ×10^5	φ_t	t-τ_1, days	ε_{be} ×10^5	ε_{pl} ×10^5	φ_t	t-τ_1, days	ε_{be} ×10^5	ε_{pl} ×10^5	φ_t
1	75.6	27	0.36	1	71.8	17.2	0.24	1	69.0	10.3	0.15
3		44	0.59	3		28.7	0.40	3		17.3	0.25
5		63	0.83	5		40.2	0.56	5		24.1	0.35
7		74	0.98	7		48.1	0.67	7		30.3	0.44
10		88	1.17	10		60.3	0.84	10		41.4	0.60
20		104	1.38	20		76.82	1.07	20		60.0	0.87
30		120	1.59	30		94.1	1.31	30		81.4	1.18
45		152	1.79	45		109.1	1.52	45		97.9	1.42
60		163	2.00	60		122.7	1.71	60		109.7	1.59
90		179	2.15	90		132.8	1.85	80		118	1.71
120		186	2.24	120		142.1	1.98				
150			2.36								
220			2.46								

CONCLUSIONS

As a result of work, a new material was obtained — non-autoclave ash porous concrete (NAPC) with density 1600-1700 kg/m^3 based on the use of gas-concrete technology, but with less gas-forming additives. This concrete of compressive strength class B15 and prism strength of 11.4 MPa is quite an effective construction material. Using NAPC, the weight of the structure can be reduced by 40% compared to elements made of heavy concrete. Strength and deformation characteristics of NAPC are determined both at short-term and long-term active loads, which is the basis for further research on the use of this per-special material in bearing and enclosing structures.

In the future, the research should concern: 1) the improvement of the production technology of NAPC, including the use of activation of ash aggregate, in order to obtain more stable and high quality indicators of the material; 2) a new and unconventional combination of structural materials such as relatively low-strength non-autoclave ash porous concrete with a density of 1600 kg/m^3 and high-strength reinforcement; 3) the research into deformability, strength, and fracture resistance of compressed reinforced elements based on non-autoclave ash porous concrete; 4) a method to determine the stress-strain state of cross-sections of structural elements under axial and eccentric compression taking into account the inelastic state of concrete, its creep and shrinkage; 5) a methodology for calculating the load-carrying capacity of structures on the basis of NAPC; 6) primary technical and economic calculations on the efficiency of production and operation of new load-bearing and enclosing structures based on NAPC for construction and reconstruction of buildings of various purposes.

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